

Balancing Radiation Dose Reduction and Image Quality in Chest Computed Tomography using Silicon Rubber-barium Sulfate Composite Shield

Abstract

Background: During chest CT examinations, the breasts are exposed to a significant amount of radiation, increasing the risk of radiation-induced cancers. The objective of this study is to develop and evaluate a novel silicon rubber-barium sulfate (BaSO₄) composite breast shield for reducing radiation dose in chest computed tomography (CT) examinations while minimizing impact on image quality. **Methods:** Four breast shields were fabricated: one with 10% bismuth and three with 10%, 15%, and 20% BaSO₄. Dose reduction was assessed using a thorax phantom and ionization chamber. Image quality effects were evaluated in the thorax phantom by measuring noise and CT number changes. The 10% barium shield was further tested on 22 patients undergoing chest CT. **Results:** The 10%, 15%, and 20% barium shields reduced breast dose by 36.8%, 38.6%, and 45.6%, respectively, while the 10% bismuth shield achieved a 63.1% reduction. However, the 10% barium shield had minimal impact on image quality, increasing lung noise by only 0.3 Hounsfield units (HU) and shifting CT numbers by 4.7 HU. In patient studies, 81.8% of scans showed no artifacts, with 18.2% showing slight artifacts. **Conclusion:** The 10% BaSO₄ shield effectively reduced breast dose while maintaining image quality, presenting a viable alternative to bismuth shielding for radiation protection in chest CT examinations.

Keywords: Barium sulfate, breast, computed tomography, dose reduction, shielding

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Introduction

Computed tomography (CT) has become an invaluable diagnostic tool in modern medicine, providing detailed cross-sectional images of the human body.^[1] However, the ionizing radiation used in CT scans raises concerns about potential health risks, particularly for radiosensitive organs such as the breasts.^[2] During chest CT examinations, the breasts are exposed to a significant amount of radiation, increasing the risk of radiation-induced cancers.^[3]

For example, Lahham *et al.*,^[4] by collecting data from 10 hospitals, reported that a single chest CT examination can deliver a dose of 6.5–28 mGy to the breast tissue and estimated the breast cancer risk for younger females to be approximately 0.05%. To mitigate this risk, various breast dose reduction techniques have been explored,^[5,6] aiming to reduce the radiation dose to the

breast tissue while maintaining diagnostic image quality.

One promising approach is the use of bismuth shielding, which has been shown to effectively attenuate low-energy X-rays. However, bismuth shields can cause artifacts and beam hardening effects, compromising image quality.^[7] Alternatively, composite materials containing elements with high atomic numbers and high attenuation coefficients have been investigated for their shielding capabilities.^[8,9]

Silicone rubber, a cost-effective elastomeric polymer containing polysiloxane unit, may be served as the primary constituent of radiation shielding materials. Its versatility stems from its exceptional characteristics, including thermal resistance, superior elasticity, low toxicity levels, chemical stability, electrical insulating properties, and resistance to abrasion. These desirable properties contribute to the

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widespread adoption of silicone rubber across numerous applications.^[10] Mehnati *et al.*^[11] developed a nanobismuth shield by incorporating bismuth nanoparticles into silicone rubber. They found that using nanobismuth oxide shields with varying bismuth concentrations and thicknesses could reduce the breast dose.

Barium sulfate (BaSO₄) has emerged as a promising alternative to lead for shielding in X-ray examinations. This compound offers several advantages, including superior X-ray absorption capabilities, relative inertness, nontoxicity, environmental friendliness, and harmlessness to the human body. In addition, BaSO₄ can be easily incorporated into other compounds. Notably, BaSO₄ possesses a high radiation absorption coefficient, making it an effective absorbent material for shielding against X-rays and gamma rays without the need for lead-based solutions.^[12] Lee and Kweon^[12] reported that in CT scans, the use of barium-based shielding agents resulted in a dose reduction of 3.3%–12.4% in the head and 3.62%–33% in the chest.

While bismuth shields are already commercially available and widely used in CT examinations, the cost and limited availability of bismuth powder remain significant drawbacks. In contrast, BaSO₄ shows potential as an alternative due to its greater accessibility and cost-effectiveness. In this study, we propose a novel shielding material composed of silicon rubber and BaSO₄ for breast dose reduction during chest CT examinations. The combination of these two materials may offer an inexpensive effective shielding solution while minimizing the risk of image artifacts.

In this paper, we present the fabrication of the silicon rubber-BaSO₄ breast shield, as well as an evaluation of its shielding performance and its impact on image quality in chest CT examinations using phantom and clinical studies.

Materials and Methods

Shields construction

In this research, four breast shields with the thickness of 4 mm were made with the following compositions: one with 10% weight percentage of bismuth (10% Bi), and three with BaSO₄ at 10%, 15%, and 20% weight percentages (10% Ba, 15% Ba, and 20% Ba, respectively).

The specified amounts of bismuth and BaSO₄ were weighed out and then combined with silicone rubber separately. A mechanical stirrer was used to thoroughly blend the components, resulting in a uniform mixture. Next, a hardening agent (at a ratio of 50 g per/kg of silicone) was incorporated into the blend. The resulting compound was then transferred into a mold. After a 24-h period, the fully formed shield was extracted from the mold. It should be noted that the mold was rectangular in shape, made of Perspex, and measured 15 cm² × 15 cm² to cover one breast.

Assessment of dose reduction

To assess the efficacy of breast shields in decreasing radiation exposure, we employed a thorax phantom along with a pencil ionization chamber dosimeter (Piranha model from RTI electronics, Sweden), as illustrated in Figure 1.

The study utilized a thorax phantom designed to mimic the electron density of human thoracic structures. It comprised three main components: cork, with Hounsfield units (HU) ranging from -774 to -841 HU, simulated the lungs; plexiglass, measuring 80–171 HU, represented soft tissues; and dense fiber (specifically, a phenolic resin cotton fiber rod) with HU values between 565 and 717 substituted for vertebral bones.^[13] Furthermore, the study included two breast phantoms, each measuring 160 mm in diameter and 80 mm in height. These phantoms were constructed using silicone materials, with a 2% catalyst.^[14] When positioning the breast phantoms, they were carefully placed to accurately replicate the natural position of breasts on the chest wall.

Radiation dose was measured in two scenarios: with and without the shields in place. To ensure accuracy, each measurement was conducted three times. When assessing the dose with shields present on the right breast, the dosimeter was positioned directly beneath the shield, specifically on the nipple area of the breast phantom.^[14]

Assessment of image quality in phantom

To evaluate the effect of shields on image quality, the thorax phantom was also used to assess both the noise and the CT number accuracy. This study evaluated image noise by calculating the standard deviation of attenuation values (measured in HU) within uniform areas of the phantom: right breast, left breast, anterior chest wall, and lung. It should be noted that three regions of interest (ROIs) were drawn in each mentioned area [Figure 1]. The average pixel values within these ROIs were used to determine the mean CT number, while their standard deviation represented the noise. To ensure accuracy, these calculations were performed across three consecutive images for each ROI, and the results were then averaged.

A 16-slice CT scanner (Somatom Emotion, Siemens, Germany) was used to simultaneously evaluate dose

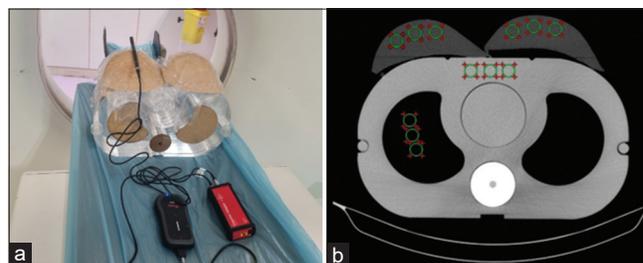


Figure 1: (a) Thorax and breast phantoms on the computed tomography (CT) scanner couch and pencil ionization chamber placed over breast phantom. (b) A CT scan image of the thorax phantom and circular regions of interest in different areas

reduction and image quality in the phantom. The thorax protocol was employed with settings of 130 kVp, 90 effective mAs, and a 5 mm slice thickness. The automatic exposure control (AEC) was on for all measurements, and the shields were positioned on the phantom after the scanogram was obtained.

Assessment of image quality in patient study

To further validate the breast shield's efficacy, the research was extended to include human subjects. The study obtained approval from the regional ethical committee (IR.GMU.REC.1401.112). Following an explanation of the study's objectives to all participants, informed consent was obtained from each of them.

The shield that demonstrated the minimal impact on image quality during the phantom study was chosen for this phase. In the human trial, this selected shield was applied to the left breast of 22 patients scheduled for chest CT scans. Consequently, the patients' left breasts served as the study group, while their right breasts acted as the control group.

Upon completion of the CT scans, the chest images were prepared for image quality assessment. To ensure an unbiased evaluation, the shield image was removed from the CT images. A radiologist then examined these processed images to assess their quality. The evaluation employed a three-point Likert scale, which was structured as follows: 0 = No artifact, 1 = slight artifact, and 2 = severe artifact.

The results of image noise and CT number were summarized using the mean and standard deviation. A Chi-square test in SPSS Version 22.0 (IBM Corporation, Armonk, NY, USA) was utilized to analyze the differences between the study group and the control group in the human study. $P < 0.05$ was considered statistically significant.

Results

Table 1 presents the average radiation dose values (mGy) both without a shield and with various breast shields, along with the corresponding percentage reductions in dose. Without any shield, the radiation dose was 5.7 ± 0.05 mGy. When using shields with 10% Ba, 15% Ba, 20% Ba, and 10% Bi, the radiation dose was reduced by 36.8%, 38.6%, 45.6%, and 63.1%, respectively.

Results of image noise (in HU) without shield and different breast shields in different areas of the thorax phantom

Table 1: Results of mean dose values (mGy) without shield and with breast shields

| Shield | Mean dose (mGy) | Dose reduction (%) |
|----------------|-----------------|--------------------|
| Without shield | 5.7±0.05 | - |
| 10% Ba | 3.6±0.06 | 36.8 |
| 15% Ba | 3.5±0.06 | 38.6 |
| 20% Ba | 3.1±0.06 | 45.6 |
| 10% Bi | 2.1±0.10 | 63.1 |

are summarized in Table 2. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, increased image noise in the right breast by 3.17, 5.63, 8.3, and 24.3 HU, respectively. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, increased image noise in the left breast by 1.04, 2.04, 5.9, and 12.74 HU, respectively. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, increased image noise in the anterior chest wall by 1.7, 2.74, 3.84, and 8.07 HU, respectively. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, increased image noise in the lung by 0.3, 0.57, 0.97, and 4.4 HU, respectively. In addition, the results of image noise are shown in Figure 2 for better comparison.

The results of CT numbers shift (in HU) are shown in Figure 2. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, changed CT numbers in the left breast by 18.0, 29.1, 37.7, and 124.2 HU, respectively. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, changed CT numbers in the anterior chest wall by 18.3, 20.2, 22.0, and 57.9 HU, respectively. 10% Ba, 15% Ba, 20% Ba, and 10% Bi shields on the right breast, changed CT numbers in the lung by 4.7, 8.1, 10.1, and 17.7 HU, respectively.

In addition, the effect of breast shields on image quality can be assessed qualitatively using CT images of the thorax

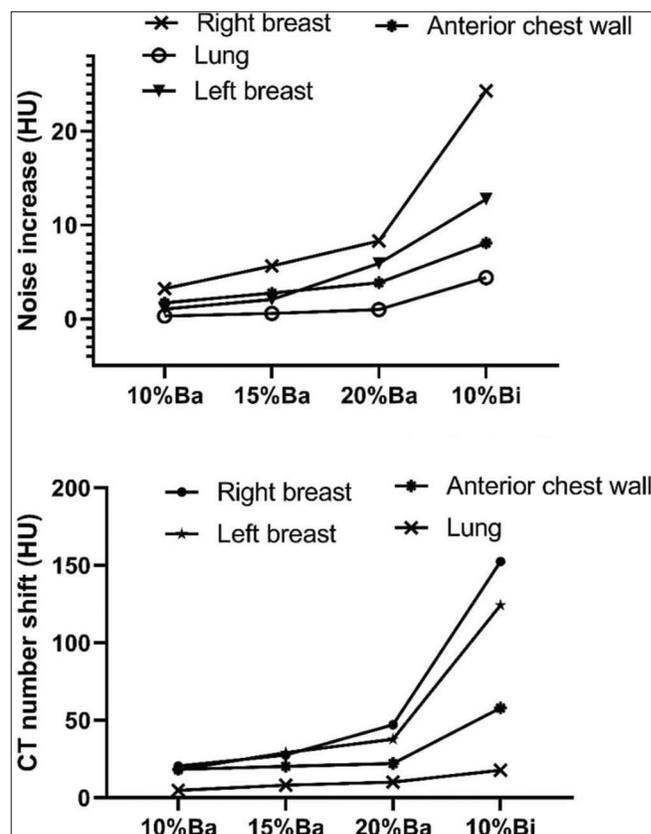


Figure 2: (Top) Increasing in image noise due to different breast shields in the thorax phantom. (Bottom) Change in computed tomography numbers due to different breast shield in the thorax phantom. HU – Hounsfield units, CT – Computed tomography

phantom [Figure 3]. It can be observed that the 10% Ba shield had a minimal impact on image quality, thus it was chosen for the human study.

The results of the human study showed that no artifacts were seen in the right breasts (control group), and no

artifacts were seen in 81.8% of the left breasts (study group). Slight artifacts were seen in 18.2% of the study group. It should be noted that no severe artifacts were seen in any of the cases. Based on the statistical evaluations conducted between the two groups, the difference was not

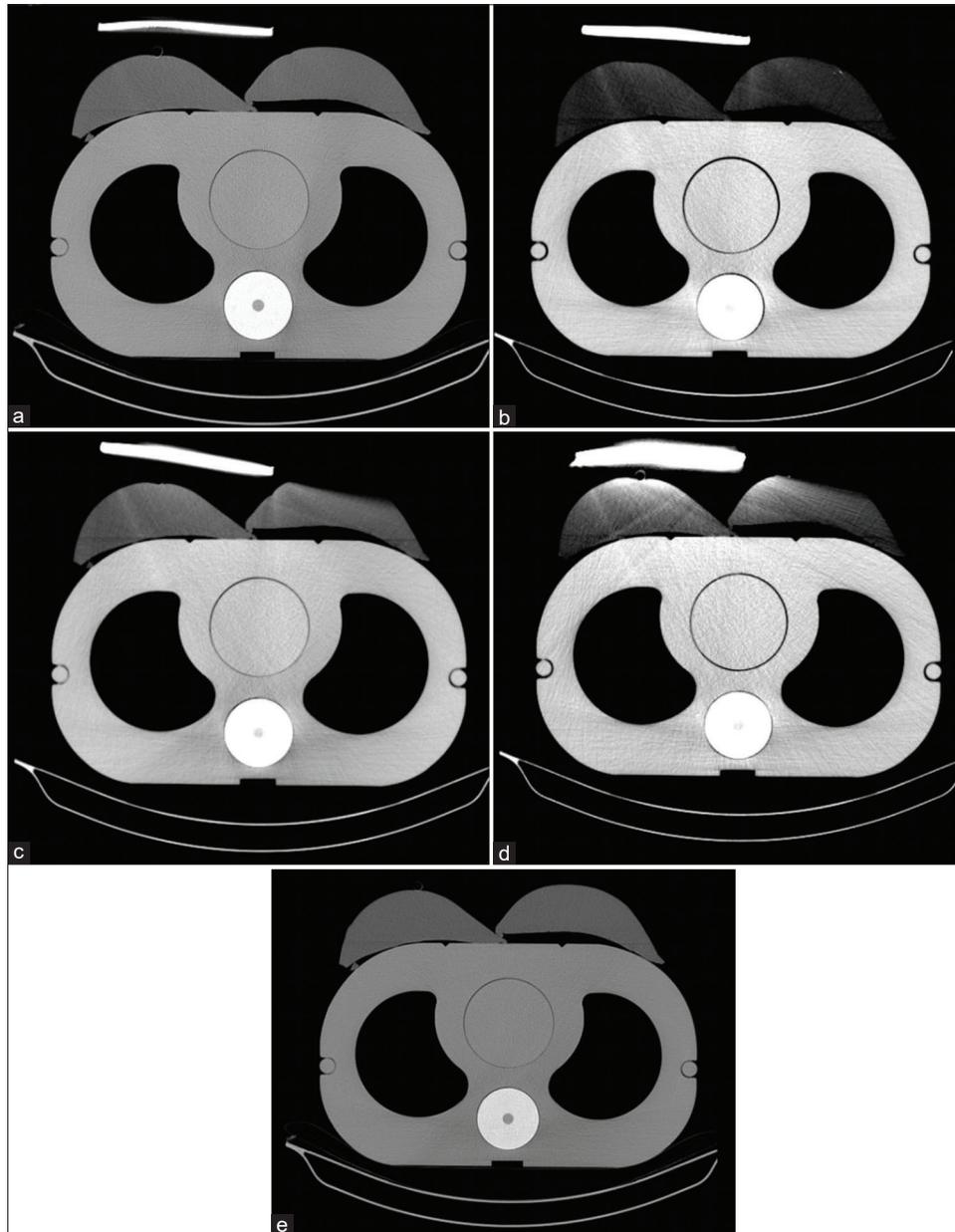


Figure 3: Effect of different shields on image quality in the thorax phantom. (a) 10% Ba shield, (b) 15% Ba shield, (c) 20% Ba shield, (d) 10% Bi shield, (e) without shield

Table 2: Results of image noise for without shield and different breast shields in different areas of thorax phantom

| Lung | Noise value (HU) | | | | |
|---------------------|------------------|------------|------------|------------|------------|
| | Without | 10% Ba | 15% Ba | 20% Ba | 10% Bi |
| Right breast | 9.80±0.26 | 12.97±1.03 | 15.43±0.29 | 18.10±0.46 | 34.10±1.25 |
| Left breast | 9.23±0.38 | 10.27±0.97 | 11.27±1.17 | 15.13±2.27 | 26.97±4.5 |
| Anterior chest wall | 13.53±0.49 | 15.23±0.50 | 16.27±0.23 | 17.37±0.51 | 21.60±2.01 |
| Lung | 9.00±0.46 | 9.30±0.46 | 9.57±0.89 | 9.97±0.55 | 13.40±1.66 |

HU – Hounsfield units

statistically significant ($P > 0.05$). In addition, one chest CT scan image from a patient using the 10% Ba shield on the left breast is shown in Figure 4.

Discussion

The good performance of the 10% Ba shield in achieving an optimal balance between dose reduction and image quality lies in its composition and material properties. At this concentration, the BaSO₄ particles provide effective attenuation of X-rays without significantly increasing image noise or causing artifacts, as observed with higher concentrations and bismuth shields. The integration of BaSO₄ into a flexible silicone matrix ensures a sufficient distribution of shielding material, maintaining consistent attenuation while avoiding adverse beam hardening. This combination enhances both shielding efficiency and usability, making the 10% Ba shield particularly suitable for clinical applications where diagnostic accuracy and patient safety are paramount. Specifically, the findings indicated that while a 10% Ba breast shield effectively reduced the dose, it had minimal impact on image quality, with lung noise levels rising by only 0.3 HU and the CT number shifting by 7.4 HU. In addition, BaSO₄ powder is more cost-effective and accessible than bismuth powder. These results imply that the barium shield could be a viable alternative to the bismuth shield for protecting breast tissue from radiation in chest CT examinations. In clinical practice, the 10% Ba shield could be easily incorporated into routine chest CT examinations. Its lightweight and flexible design ensures patient comfort while providing effective radiation protection. In addition, the shield's cost-effectiveness makes it accessible for widespread use, particularly in low-income countries.

The study's results demonstrated that increasing the percentage of BaSO₄ as a protective material enhanced breast dose reduction. This finding aligns with Mehnati *et al.*,^[11] who reported that higher percentages of bismuth



Figure 4: Chest computed tomography scan image from a patient using the 10% Ba shield on the left breast

in breast shields improved protection efficacy. The primary goal of radiation protection in medical imaging is to use the lowest possible dose to achieve accurate diagnoses. With the growing use of CT scans in medical diagnostics, sensitive organs such as women's breasts are exposed to higher radiation levels, making dose reduction for these organs a critical consideration.

Several studies have investigated the use of bismuth and other shields for dose reduction in chest CT examinations.^[11,14,15] Lee and Kweon^[16] developed a barium composite shield that reduced the dose in a chest phantom by 3.62%–33%, but it also increased image noise by up to 90.66%.

Mehnati *et al.*^[11] reported that a 1-mm thick shield containing 15% nanobismuth reduced breast dose by 24%, while it increased image noise in the central region of a female thorax phantom by 10%. In comparison, the proposed 10% Ba shield in our study reduced breast dose by 36.8% and increased image noise in the lung region of a female thorax phantom by only 3.33%, indicating superior safety and efficacy of the barium shield. Although the 10% Bi shield decreased the dose more than the BaSO₄-based shields due to the higher attenuation efficacy of bismuth, it remarkably degraded image quality, as observed by severe artifacts in the CT images of the thorax phantom. This necessitates the concurrent evaluation of dose reduction efficacy and image quality.

Lestari *et al.*^[14] found that silicone rubber-lead shields of different thicknesses reduced breast dose by 8%–38%, but increased breast noise by 4%–26% and changed CT numbers by 22.8–33.4 HU. Our study revealed that a 10% Ba shield increased breast noise by 32.3% and changed CT numbers by 20.4 HU, consistent with the findings of Lestari *et al.* However, it should be noted that BaSO₄ presents distinct advantages over lead, including its relative inertness, nontoxicity, environmental friendliness, and safety for the human body.

Ko *et al.*^[17] reported in a patient study that bismuth shielding can reduce breast dose by 11.65% if applied before the scanogram and 27.99% if applied after the scanogram during a chest CT examination. The 10% Ba breast shield developed in our study demonstrated superior dose reduction efficacy, achieving a 36.8% reduction when placed on the phantom after the scanogram. The AEC system adjusts the scanner's output dose based on patient anatomy and attenuation to obtain high-quality images with minimal exposure. To achieve this, the scanner takes a radiograph of the patient before beginning the scan. Placing the shield before this radiograph can cause the tube current to increase, negating the shield's dose-reduction benefits. Therefore, to maximize dose reduction, the shield should be placed on the patient's organ after obtaining the scanogram.

The results of this study showed that moving away from the shield decreases image noise and CT number shifts. For

instance, with the 10% Ba shield, the increases in image noise for the right breast, anterior chest wall, and lung were 3.17, 1.7, and 0.3 HU, respectively. This finding is consistent with our previous report,^[15] which showed that CT number shifts and image noise decreased rapidly with increasing distance between the shield and the ROI in a CTDI phantom. Therefore, placing a spacer, such as foam, between the shield and the body surface can significantly preserve image quality, as demonstrated in this study with a 2-cm foam spacer in patient studies.

The American Association of Physicists in Medicine advises considering alternative methods to minimize radiation exposure to radiosensitive organs, due to the adverse impact of bismuth on image quality and the potential for increased radiation dose when used alongside AEC.^[18] Although organ-based tube current modulation (OBTCM) effectively reduces dose without degrading image quality in CT scans, there are significant concerns associated with its use. These include an increase in the dose to posterior organs and the risk of unwanted exposure if the patient is not properly centered. Furthermore, OBTCM requires specialized training for technologists and the process of adjusting the patient can be time-consuming. It is also more expensive than using physical shields and may not be available on all CT scanners, particularly in low-income countries where older generation scanners are more common.^[15] In addition, the dose reduction achieved by OBTCM is generally less effective compared to shielding techniques.^[19] Musmann *et al.* found that OBTCM in GE CT scanners and Canon systems decreased the breast dose in a Lungman phantom by 12%–24% and 6%–10%, respectively.^[18]

This study has certain limitations that should be addressed. First, the absence of thermoluminescent dosimeters (TLDs) in dose measurement represents a limitation. TLDs are widely used for accurate point dose measurement, and their absence may impact the precision of dose assessments. Second, the relatively small sample size of 22 patients limits the generalizability of the findings. This small number may not adequately represent variations across diverse patient sizes and settings of CT exposure factors. Future studies with larger patient populations and the inclusion of TLDs could strengthen the validity and generalizability of these findings. In addition, the effectiveness of dose savings from the simultaneous use of a 10% Ba shield and OBTCM was not investigated.

Conclusion

Our study demonstrates that the novel silicon rubber-BaSO₄ shield is a cost-effective solution for reducing breast dose in chest CT examinations. Specifically, the 10% BaSO₄ shield achieved a significant 36.8% dose reduction while maintaining minimal impact on image quality. Compared to bismuth shields, the BaSO₄ shield offers a superior balance between dose reduction and image clarity. Notably, 81.8% of patient scans using the 10% BaSO₄ shield showed no

artifacts, underscoring its reliability and potential for widespread clinical use.

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Conflicts of interest

There are no conflicts of interest.

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